to appear in the Astrophysical Journal Letters.
Preprint typeset using LaTeX style emulateapj v. 14/09/00

CHANDRA OBSERVATION OF THE RADIO SOURCE / X-RAY GAS INTERACTION IN THE COOLING FLOW CLUSTER ABELL 2052

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ABSTRACT

We present a *Chandra* observation of Abell 2052, a cooling flow cluster with a central cD that hosts the complex radio source 3C 317. The data reveal "holes" in the X-ray emission that are coincident with the radio lobes. The holes are surrounded by bright "shells" of X-ray emission. The data are consistent with the radio source displacing and compressing, and at the same time being confined by, the X-ray gas. The compression of the X-ray shells appears to have been relatively gentle and, at most, slightly transonic. The pressure in the X-ray gas (the shells and surrounding cooler gas) is approximately an order of magnitude higher than the minimum pressure derived for the radio source, suggesting that an additional source of pressure is needed to support the radio plasma. The compression of the X-ray shells has speeded up the cooling of the shells, and optical emission line filaments are found coincident with the brightest regions of the shells.

Subject headings: galaxies: clusters: general — cooling flows — intergalactic medium — radio continuum: galaxies — X-rays: galaxies: clusters

1. INTRODUCTION

The very central regions of clusters of galaxies are among the most active physical environments in the Universe. In a significant fraction of clusters ("cooling flows"), large amounts of gas ($\sim 10^2\ M_\odot\ \mathrm{yr}^{-1}$) are cooling radiatively from $\sim 10^8$ to $\sim 10^7$ K, making these regions extremely bright X-ray sources (see Fabian [1994] for a review). Cooler gas is seen through optical emission lines. There is always a large (cD) galaxy at the center of these cooling flow clusters, and the majority of these galaxies are hosts of radio sources. It may be that the cooling gas acts as fuel for the accreting central black hole, thus helping to produce the radio emission. Recent *Chandra* images have shown that the radio sources and X-ray gas are interacting; examples include Hydra A (McNamara et al. 2000; David et al. 2001) and Perseus (Fabian et al. 2000). In both of these cases, there is an anti-coincidence between the radio and X-ray emission, such that the radio lobes are found in regions where there are "holes" in the X-ray emission. Depressions in the X-ray emission at the locations of radio emission are also seen with *Chandra* for Abell 2597 (McNamara et al. 2001).

Abell 2052 is a moderately rich, cooling flow cluster at a redshift of $z = 0.0348$. The central cD galaxy, UGC 09799, hosts the complex, powerful radio galaxy 3C 317. Previous X-ray observations with *Einstein* (White, Jones, & Forman 1997), *ROSAT* (Peres et al. 1998), and *ASCA* (White 2000) have shown that Abell 2052 has an average temperature of approximately 3.3 keV, and contains a cooling flow with a cooling rate of $\dot{M} \approx 120\ M_\odot\ \mathrm{yr}^{-1}$. *ROSAT* and *VLA* images revealed excess X-ray emission surrounding much of the radio source (Rizza et al. 2000).

In this *Letter*, we discuss a *Chandra* observation of Abell 2052 which shows a dramatic interaction between the radio source and X-ray emission. We will present a more detailed study of Abell 2052, based on this data, in a future paper. We assume $H_\circ = 50$ km s^{-1} Mpc^{-1} and $q_\circ = 0.5$ ($1'' = 0.95$ kpc at $z = 0.0348$).

2. OBSERVATION AND DATA REDUCTION

Abell 2052 was observed with *Chandra* on 2000 September 3 for a total of 36,754 seconds. The observation was taken so that the center of the cluster would fall near the aimpoint of the ACIS-S3 CCD. Here, we analyze data from the S3 chip only. The events were telemetered in Faint mode, the data were collected with frame times of 3.2 seconds, and the CCD temperature was -120 C. Only events with *ASCA* grades of 0,2,3,4, and 6 were included. Standard bad pixels and columns were removed. The data were searched for background flares and none were found. A small period of bad aspect was found and removed, leaving a total exposure of 36,622 seconds.

3. X-RAY STRUCTURE

Figure 1 shows an adaptively smoothed image of the central $4'.2 \times 4'.2$ region of the cluster. The smoothed image has a minimum S/N of 3 per smoothing beam and was corrected for exposure and background, the latter using the blank sky background fields from Markevitch (2000). The inner part of the cluster shows the high surface brightness characteristic of a cooling flow. At small radii, a bright ring of emission is apparent. In addition, there is a bar of enhanced X-ray emission running approximately East-West through the center. The brightest parts of the ring and bar appear to form two shells to the north and south, and the bar may be just the intersection of the two shells. These bright shells surround two holes of lowered X-ray brightness. There is also a spur of emission to the NW of the center which protrudes into the northern hole. A point source associated with the center of the cD galaxy and the

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central AGN is located above the center of the bar. Several other point sources are also evident in Figure 1. All of these features are easily seen in the raw image prior to any smoothing, background subtraction, or exposure corrections.

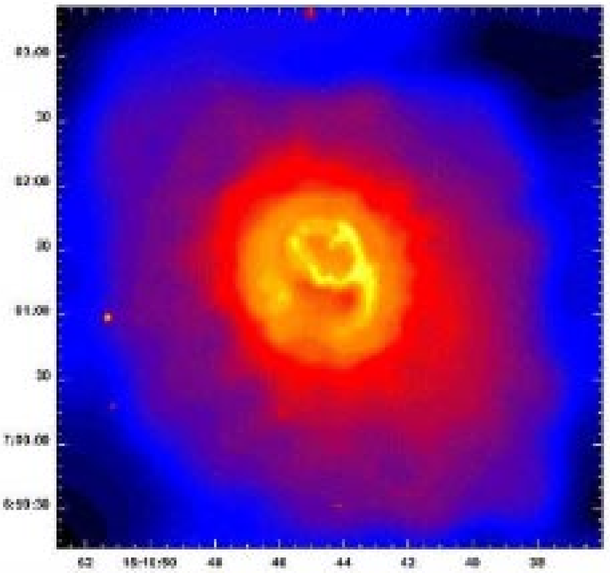

FIG. 1.— An adaptively smoothed image of the 4.′2×4.′2 region surrounding the center of Abell 2052. The image has been corrected for background and exposure. The color scale is logarithmic and ranges from 2.5×10^{-6} to 1.1×10^{-2} ct pix^{-1} s^{-1}.

Figure 1 gives the impression that the two holes in the X-ray image are relatively empty regions surrounded by dense shells of gas, and that the shells are limb-brightened. To test this, we determined the surface brightness in the centers of each of the holes. From the deprojection of the X-ray surface brightness discussed below, we estimated the X-ray brightness expected if the holes were indeed empty, were centered at the same distance as the AGN, and all of the X-rays were due to projection. This gave a predicted central surface brightness of 1.5 ct s^{-1} arcmin^{-2}, whereas the observed values are 1.5 (1.3) ct s^{-1} arcmin^{-2} for the northern (southern) hole. As a further test, we determined the mass for the southern shell, assuming it is spherical and taking the density from deprojection. We compared this mass to the total mass predicted to be within the volume of the shell by extrapolating the deprojected density distribution outside of the disturbed region into these radii. For the southern shell, the observed mass is $6 \times 10^{10}\ M_{\odot}$, whereas the predicted mass is $(9 \pm 5) \times 10^{10}\ M_{\odot}$ depending on how the density distribution is extrapolated. Thus, these numbers are consistent with the idea that the holes are devoid of X-ray emitting gas, and that the missing gas was pushed out of the holes and compressed into the shells.

To understand and model the structure in the inner regions of the cluster, we extracted the X-ray surface brightness (Fig. 2a), and spectra in twenty circular annuli centered on the central point source, with radii ranging from 4.″7 to 226″. Each spectrum typically contained several thousand source counts and was fitted with a single temperature MEKAL model with the absorption fixed to the Galactic value ($N_H = 2.85 \times 10^{20}$ cm^{-2}; Dickey & Lockman 1990). Background was taken from the blank sky fields (Markevitch 2000). The fits reveal that the gas has cooled to a temperature of $kT \approx 1.4$ keV at the center compared to the value of approximately 3.4 keV found for the outer annuli (Fig. 2c).

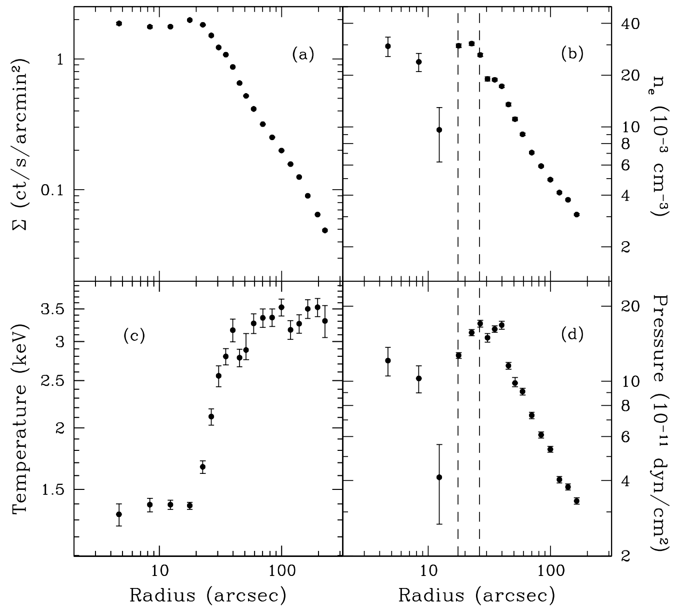

FIG. 2.— Surface brightness (a), electron density (b), temperature (c), and pressure (d), as a function of radius. The vertical dashed lines mark the mean inner and outer radii of the bright X-ray ring.

The surface brightness values for the band 0.3–10 keV were deprojected to determine the X-ray emissivity and gas density (Fig. 2b), assuming the emissivity is constant in spherical shells. The density and temperature measurements where used to determine the radial variation in the pressure in the gas (Fig. 2d), assuming the temperature in the projected spectrum fit is the temperature at that spherical radius. Outside of the brightened shell of X-ray emission, the pressure exhibits a smooth, monotonic decrease with increasing radius, which is presumably the result of nearly hydrostatic equilibrium. There is a nearly constant pressure ($P \approx 1.5 \times 10^{-10}$ dyn cm^{-2}) at radii corresponding to the bright ring of X-ray emission and just outside it. Interior to the ring, the pressure is lower and shows large oscillations. This is the result of the complex, non-circularly symmetric structure (the holes, bar, and spur) within this region, and the spherically averaged pressure is not meaningful.

In order to better determine the pressure in the brightest regions of the ring of emission, we measured the pressure in a pie-annular region of the bright ring located to the West of the center of the cluster. The surface brightness was measured for the region and corrected for background taken just outside of the ring. We assumed that the emission in this region was part of a spherical shell of emission. A spectrum was extracted and the pressure was determined in a manner similar to that described above. In this case, the pressure was found to be $P = 1.43 \times 10^{-10}$ dyn cm^{-2}, which is consistent with the values derived assuming spherical symmetry (Fig. 2d).

4. INTERACTION WITH THE RADIO SOURCE

An overlay of the 6 cm radio contours (Burns 1990) onto the adaptively smoothed X-ray image (0.3 – 10.0 keV) of the inner region of Abell 2052 is displayed in Figure 3. There is a core source located at the center of the cD galaxy which is seen in both radio and X-ray. Most of the extended radio emission is projected within the X-ray holes to the north and south. Almost all of the radio emission is contained within the bright X-ray shells. However, there appears to be faint radio emission extending slightly beyond the shells to the south and north where the shell is faint or absent.

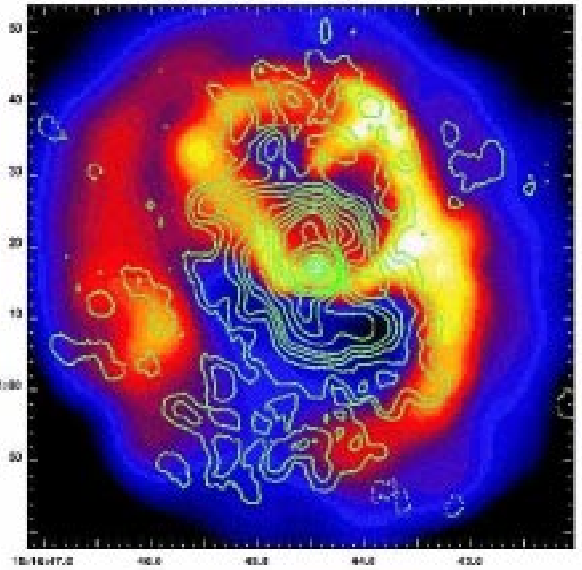

FIG. 3.— Radio contours of 3C 317 (Burns 1990) overlaid onto the adaptively smoothed *Chandra* X-ray image of the central $76'' \times 76''$ region of Abell 2052.

Figure 3 suggests that the expansion of the radio source has displaced the thermal gas which was formerly in the X-ray holes, and compressed this gas into the bright shells. As noted above, the X-ray holes do indeed appear to be devoid of X-ray emitting gas, and the mass of the shells is consistent with the mass which might have been located in the holes prior to the displacement. How violent and energetic is the expansion of the radio source? Heinz, Reynolds, & Begelman (1998) and Rizza et al. (2000) suggested the radio source would create cavities in the intracluster gas by highly supersonic expansion into the gas. Such a violent expansion would drive strong shocks into the intracluster gas. As a result of such strong shocks, the shell of X-ray gas surrounding the radio-filled cavity would have a higher temperature, pressure, and specific entropy than the gas just outside the shell. In fact, this does not appear to be true of the shells in Abell 2052, although we cannot rule out supersonic expansion by the radio source in the past when it was much younger. Our fits to the X-ray spectra indicate that the average temperature of gas in the shells is 1.1 keV, whereas the temperature of gas just outside the shells is 2.6 keV. Since the gas in the shells is denser than the gas outside the shells, the specific entropy is actually much lower than that outside the shells. Figure 2d shows that the pressure in the shells is roughly equal to that just outside the shells, and there is no evidence for a sharp increase in the pressure which would indicate the presence of a shock. The largest increase, which is still roughly consistent with the gradient in pressure associated with hydrostatic equilibrium, occurs between radii of approximately 40–45″. If we take the pressure increase at this point as an upper limit on any shock, the Mach number $\mathcal{M}$ of any shock associated with the radio source expansion must be $\mathcal{M} \lesssim 1.2$. Thus, the expansion of the radio source is subsonic or mildly transonic. Similar results have been found for the radio source cavities in Hydra A (McNamara et al. 2000; David et al. 2001) and Perseus (Fabian et al. 2000).

The relatively slow expansion of the radio source implies that the material in the radio cavity and the surrounding shell should be nearly in pressure equilibrium. Assuming equipartition of energy, Zhao et al. (1993) calculated the minimum radio pressures for several components of 3C 317 using 6 cm observations. For their radio "halo" component (the region centered on the core source with dimensions 75×45 kpc which corresponds to most of the volume of the radio-filled holes), they determined a minimum pressure of $P_{\rm min} = 2 \times 10^{-11}$ dyn cm^{-2}, approximately an order of magnitude lower than the *Chandra* value for the X-ray shells. Even for the radio "bipolar" component (a 30×15 kpc region centered on the core), they calculated a value of $P_{\rm min} = 5 \times 10^{-11}$ dyn cm^{-2}, still lower than the value derived from our X-ray observations.

Thus, it seems likely that the radio cavities contain some component with a larger pressure than given by these equipartition arguments. This may indicate that one of the basic assumptions of the standard equipartition arguments (random pitch angles, magnetic field not parallel to the line of sight, etc.) is wrong. The high degree of polarization of the radio source once corrected for Faraday rotation (Ge & Owen 1994) suggests that the latter assumption might be nearly correct. There may be a large contribution to the pressure from very low energy relativistic electrons. However, the radio spectrum of the large scale radio component is quite steep ($\alpha \approx -1.9$), so the equipartition estimates already include a large population of such particles. The steep spectrum also makes extrapolation to low energies more uncertain. However, since confined radio sources typically have curved spectra, the assumption of a power law spectrum should overestimate rather than underestimate the pressure from the radio source. The energy and pressure contribution of ions may be greater than assumed by Zhao et al. (1993); minimum energy arguments would be roughly consistent with the observed X-ray pressure if the ratio of ions to electrons was $\sim$70, rather than unity as assumed by Zhao et al. The magnetic field may be larger than the equipartition value. Finally, the nonthermal plasma may only contribute a small fraction of the total energy in the radio-filled cavities (either because the local nonthermal pressure is low or because the radio plasma is filamentary and doesn't fill the volume), with the majority of the pressure coming from very hot, diffuse thermal gas. We extracted the X-ray spectrum of the southern hole, and searched for a very hot component in the spectrum. None was seen, but the observations are not very restrictive.

Cluster cooling flows with central radio sources are useful bolometers for determining the total energy output of radio sources, since the energy is apparently confined within the radio holes by the high pressure intracluster gas rather than going into adiabatic expansion losses. Assuming that the pressure within the radio cavities is $P \approx 1.5 \times 10^{-10}$ dyn cm^{-2} and approximating the holes as spheres $\sim$20 kpc in diameter, one finds that the total energy output of the radio source (including the work done on compressing the intracluster gas) is about $E_{\rm radio} \approx 1 \times 10^{59}$ ergs. There is a factor of $\sim$2 uncertainty associated with our ignorance of the nature of the dominant energy component in the radio source (higher energy for relativistic particles, lower for magnetic fields). The assumption of near pressure equilibrium implies that this energy is comparable to the energy content of the thermal X-ray gas which filled the holes, but very small compared to the total energy content of the ICM. This suggests that individual radio sources can have dramatic effects locally, but individual radio outbursts are unlikely to have large global effects (i.e., on scales much greater than 30 kpc). On the other hand, central radio sources are found in most cooling flows, and the radio source lifetimes are much shorter than cluster lifetimes; thus, it is very likely that radio activity is episodic. The accumulated effect from repeated episodes of radio activity might affect ICM on larger scales.

The density in the radio cavities is apparently much lower than that in the ambient gas, and the holes should therefore be buoyant. They would be expected to rise out of the center of the cluster at a fraction of the sound speed in the ambient gas, or $t_{\rm buoy} \sim 2 \times 10^7$ yr. The buoyant rise time is somewhat longer than the synchrotron lifetime of the large scale radio source ($t_{\rm syn} \approx 9 \times 10^6$ yr), which is consistent with the steep radio spectrum (Zhao et al. 1993). The extended diffuse radio emission at the north and particularly the south ends of the ring and faintness of the shells in these regions may indicate that buoyancy and/or related Rayleigh-Taylor instabilities are acting there.

5. RELATION TO COOLER MATERIALS

We deprojected the surface brightness of the bright western portion of the X-ray ring, and found a density of $n_e = 0.04$ cm^{-3}. Based on the X-ray spectrum of the bright ring, the temperature in these regions is 1.1 keV. Using the best-fitting model, we find that the isobaric cooling time for the gas in the ring is $t_{\rm cool} \approx 2.6 \times 10^8$ yr. This is much shorter than the probable age of the cluster, but longer than the upper limit on the age of the radio source $t_{\rm buoy}$. Thus, it is likely that the gas in the ring is cooling, but that most of the compression is due to the expansion of the radio source rather than cooling. Note that this compression is likely to have enhanced the cooling; either adiabatic compression or compression by weak shocks ($\mathcal{M} < 6.5$ for bremsstrahlung cooling) actually speed up cooling, despite the associated heating of the gas (Lufkin, Sarazin, & White 2000; Sarazin 2001).

There is also evidence for much cooler material in the same regions. Contours of Hα + [N II] emission from Baum et al. (1988) are plotted over the smoothed X-ray emission in Figure 4. The core source is seen at these wavelengths, as well as emission running roughly East-West through the core and corresponding with the X-ray bar. There is also a component NW of the center, spatially coincident with the "spur" of X-ray emission. Given the short cooling time in these regions, it seems possible that this gas at $T \sim 10^4$ K has cooled down from X-ray temperatures, although this probably occurred before the gas was compressed by the radio source. The displacement of the gas from the higher-pressure central regions outward into lower ambient pressure would lead to adiabatic expansion, which could also contribute to cooling. In general, optical line emission is found associated with nearly all of the very brightest regions of X-ray surface brightness. This suggests that the Hα + [N II] image may be surface-brightness limited, and that a deeper emission line image would detect emission from other parts of the X-ray-bright ring.

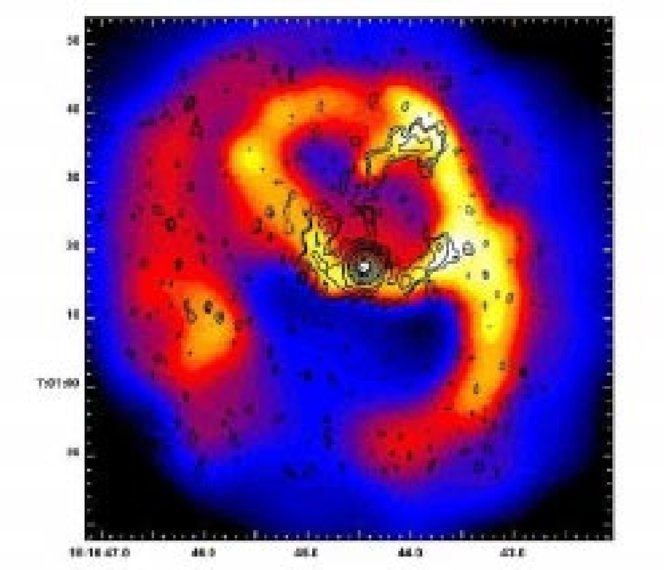

FIG. 4.— Overlay of the Hα + [N II] contours from Baum et al. (1988) onto the *Chandra* X-ray image. The Hα + [N II] emission is coincident with the brightest part of the X-ray ring, consistent with the X-ray spectral observations that cooling is occurring in these regions.

Support for this work was provided by the National Aeronautics and Space Administration, primarily through *Chandra* Award Number GO0-1158X, but also through GO0-1019X and GO0-1173X, all issued by the *Chandra* X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-39073.

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